Journal of Power Sources 262 (2014) 169–177

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Primary and secondary use of electric mobility batteries from a life cycle perspective

Ricardo Faria [a,*], Pedro Marques [b], Rita Garcia [b], Pedro Moura [a,*], Fausto Freire [b], Joaquim Delgado [a], Aníbal T. de Almeida [a]

[a] Institute of Systems and Robotics, Dept. of Electrical and Computer Engineering, University of Coimbra, 3030-290 Coimbra, Portugal
[b] ADAI–LAETA, Dept. of Mechanical Engineering, University of Coimbra, 3030-788 Coimbra, Portugal

HIGHLIGHTS

- A life-cycle assessment of primary and secondary use of EV batteries is performed.
- Three scenarios of battery use in an EV are assessed, characterized by C-rate.
- Two residential energy storage strategies are analyzed: peak shaving and load shifting.
- Cycling the battery at 0.4C in the EV results in 42–50% less impacts per km than at 0.8C.
- Benefits of extending the life of the battery strongly depend on the electricity mix.

ARTICLE INFO

Article history:
Received 1 December 2013
Received in revised form
7 March 2014
Accepted 20 March 2014
Available online 1 April 2014

Keywords:
Battery electric vehicles
Environmental impacts
Life-cycle assessment
Lithium-ion batteries
Stationary energy storage

ABSTRACT

With age and cycling, batteries used in Electric Vehicles (EVs) will reach a point in which they will no longer be suitable for electric mobility; however, they still can be used in stationary energy storage. This article aims at assessing the Life-Cycle (LC) environmental impacts associated with the use of a battery in an EV and secondly, at assessing the LC environmental impacts/benefits of using a battery, no longer suitable for electric mobility, for energy storage in a household. Three electricity mixes with different shares of renewable, nuclear and fossil energy sources are considered. For the primary battery use, three in-vehicle use scenarios are assessed, addressing three different driving profiles. For the secondary use, two scenarios of energy storage strategies are analyzed: peak shaving and load shifting. Results show that a light use of the battery in the EV has 42–50% less impacts per km than an intensive use. After its use in the vehicle, the battery life can be extended by 1.8–3.3 years; however, this is not always beneficial from an environmental point of view, since the impacts are strongly dependent on the electricity generation mix and on the additional efficiency losses in the battery.

1. Introduction

Improvements in battery technology are likely to make possible the widespread use of Electric Vehicles (EVs) for personal mobility, since they are seen as one of the solutions to reduce global Greenhouse Gas (GHG) emissions, improve air quality, reduce crude oil dependence and increase energy security. The penetration rate of EVs is increasing and is expected that in the future a large share of vehicles will be battery powered [1–4]. Nowadays, both Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) use lithium ion batteries with a significant size/weight and capacity (from 10 kWh up to 85 kWh). These are responsible for a significant contribution to the overall emissions and energy consumption associated with the manufacturing and disposal phase of the vehicle [5,6].

Despite the fact that battery packs used in EVs are managed by a Battery Management System (BMS), to ensure that they operate within safe parameters and to maximize their life [7], these packs will reach a point when they will no longer be suitable to be used in an EV. When the capacity loss is so high, that the normal use of the vehicle is affected in terms of distance traveled per charge, the battery pack should be replaced.

* Corresponding authors.
E-mail addresses: rfaria@isr.uc.pt, ricardompfaria@gmail.com (R. Faria), pedro.marques@dem.uc.pt (P. Marques), rita.garcia@dem.uc.pt (R. Garcia), pmoura@isr.uc.pt (P. Moura), fausto.freire@dem.uc.pt (F. Freire), jdelgado@estv.ipv.pt (J. Delgado), adealmeida@isr.uc.pt (A.T. de Almeida).

http://dx.doi.org/10.1016/j.jpowsour.2014.03.092
0378-7753/

Giving a second life to a battery pack, no longer suitable for electric mobility, may bring environmental and economic benefits by extending the service life of the pack, since there is some capacity still available [8,9]. The use of a battery for energy storage in buildings tens to contribute to a more constant load diagram and may mitigate the environmental impacts associated with energy consumption, by storing energy from generation periods with lower impacts and using it in periods where energy production would have higher impacts (for instance, charging the battery at night, when the contribution from Renewable Energy Sources (RESs) is usually higher and supplying it during the day, when the contribution from fossil powered power plants is higher).

The objective of this article is two-fold: firstly, it aims at assessing the LC environmental impacts of a lithium-ion battery used in an EV (primary use); secondly, it aims at assessing the LC environmental impacts, or benefits, of using a lithium-ion battery, no longer suitable for electric mobility, for energy storage in buildings (secondary use). For the primary use, three in-vehicle use scenarios are assessed, which address three different driving profiles in terms of the stress imposed to the battery. For the secondary use, two scenarios of energy storage strategies are assessed: peak shaving and load shifting. Moreover, since environmental impacts in both primary and secondary use are influenced by electricity generation, several mixes within the European Union, with different shares of renewable, nuclear, and fossil energy sources, are considered. By assessing different electricity mixes and energy storage strategies, it is possible to identify the scenarios that are potentially more beneficial in terms of environmental impacts. The reminder of the paper is structured as follows: on Section 2 the life-cycle model for both primary and secondary use of the battery is presented, as well as the battery use scenarios for each application; on Section 3 the life cycle environmental impacts associated with both use phases are assessed; and on Section 4 conclusions are drawn.

2. System models and usage scenarios

The assessment of the environmental impacts of both primary and secondary use of the EV lithium-ion battery is performed by applying the Life-Cycle Assessment (LCA) methodology [10,11]. LCA is widely used to assess the environmental performance of products or systems, including batteries and electric vehicles [5,6,12–14]. It covers all the stages of a product life cycle, from raw material extraction to final disposal, including production of the product, distribution and use, and usually assesses several environmental indicators. In this article, the environmental impacts are assessed for the following impact categories from CML 2001 baseline [15]: Abiotic Depletion; Acidification; Eutrophication; and Global Warming.

Table 1
Efficiency along the electricity path, using a standard 240 VAC charger (L2), with lithium-ion batteries as energy storage. It should be noted that, for the overall system efficiency, the battery efficiency was accounted twice due to the charge and discharge cycles.

	Efficiency (%)
Transmission	98
Distribution	92
L2 Charger	96
Battery (L2 Charge/discharge)	90/95
Inverter	95

2.1. Life-cycle model of battery primary use - electric mobility

The system boundary of the battery LC model for the assessment of the environmental impacts from its primary use (in an EV) is presented in Fig. 1. The model includes the production of all battery components and the battery end-of-life, as well as electricity generation for vehicle operation. The functional unit is 200000 km, which is the predicted service life of the vehicle [16]. The number of batteries required to perform that function (i.e. the reference flow as described by the LCA methodology) depends on the conditions under which the battery is used. In order to capture different levels of stress imposed to the battery, three driving profiles are assessed, described in detail in Section 2.1.1.

The battery pack characteristics considered in the assessment, in terms of capacity and battery chemistry, are those from the Nissan Leaf battery. The battery pack uses Lithium Manganese Oxide (LMO) for the cathode material and graphite for the anode material. The main characteristics of the battery pack has a design capacity of 24 kWh with a cell specific energy of 114 Wh kg^{-1} and a total weight of 300 kg (more details in Table S-A.11 in the Supplementary data). A life-cycle inventory for the battery production is implemented, based on [17]. Recycling of the battery at the end-of-life (EoL) is assumed to be performed through a hydrometallurgical process [18], and data for the life-cycle inventory is based on [19]. The energy required for the battery dismantling is also taken into account, according to [20]. The production of the vehicle is not considered, since environmental impacts are the same for all scenarios addressed.

Impacts of the use phase (vehicle operation) are calculated taking into account the electricity mix impacts for the period of the day during which the battery is being charged. Two scenarios are considered for EV charging: at night (00:00–07:00) and during the

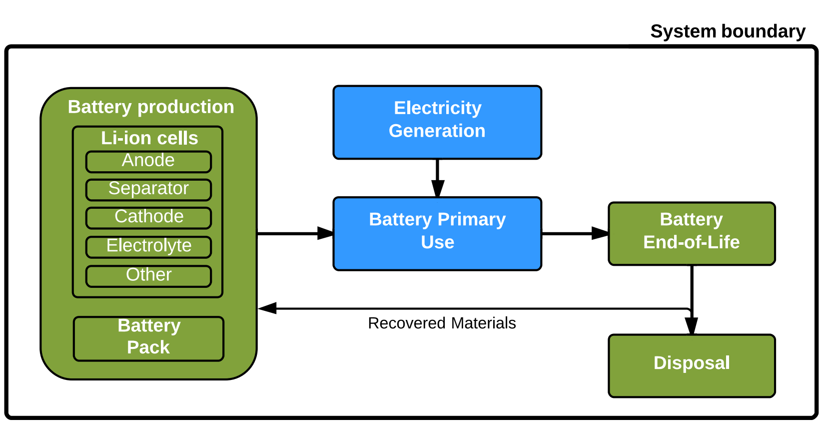

Fig. 1. System boundary of the battery life-cycle model for primary use (electric mobility).

Table 2
Energy consumption and estimated range for the Nissan Leaf based on the driving style and climate control settings based on data acquired from several runs in an urban and suburban environment.

Driving style	AC OFF		AC ON cool.		AC ON Heat.	
	Wh km^{-1}	C-Rate	Wh km^{-1}	C-Rate	Wh km^{-1}	C-Rate
Aggressive	155.4	0.58	177.7	0.65	213.4	0.80
Normal	131.0	0.50	151.0	0.57	182.8	0.67
ECO	104.7	0.40	129.0	0.49	167.1	0.60

day (09:00–17:00). The LC modeling of electricity generation is presented in a separate Section (Section 2.3), since electricity generation is common to both primary and secondary use of the battery.

2.1.1. Driving profile scenarios

Battery life and capacity are key aspects for the assessment of the environmental impacts associated with its use. Thus, it is fundamental to estimate the life of the battery under real world operation. The battery State of Health (SoH) is greatly influenced by the load and environmental conditions [21,22], and, depending on the lithium-ion cell chemistry, both high and low State of Charge (SoC) contribute to the deterioration of the battery performance and lifetime. Overcharge, over-discharge, high Depth of Discharge (DoD) and high temperatures also influence the fast decay of the battery life and low temperatures can also have a negative impact, mainly during the charging phase [23–25].

The aging of a battery occurs due to the electrochemical degradation processes that takes place during the operation and also during rest periods, where energy is not being drawn from the battery pack. The aging process leads to an increase of the internal resistance and self discharge rate and to a reduction of capacity [26,27].

The calendar aging is mainly driven by the loss of active lithium ions due to solvent reduction reaction and the rise of the anode film resistance [28]. The capacity fade due to aging is irreversible and is proportional to the square root of time [29]. The temperature also affects the calendar aging, following the Arrhenius Law, where the temperature contribution is exponential. Increasing the temperature by 10 °C will approximately double the degradation rate. The SoC also contributes to the aging process in a similar way to the aging process according to [30,31]. To reduce the calendar aging during a long storage period, a cool environment with a SoC around 40% is recommended. The cycle aging corresponds to a capacity fade due to the use of the battery and is affected by the depth of discharge in a non-linear way. Partial discharge cycles will contribute to a lower capacity loss when compared with full discharge cycles [29,32].

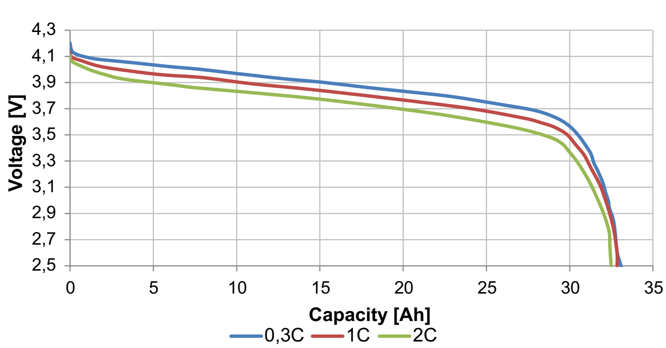

Fig. 2. Capacity variation for several discharge profiles, for a Nissan Leaf battery pack cell, under different loads. For a fresh cell, under a discharge current of 0.3C, the cell can store 32.5 Ah [33].

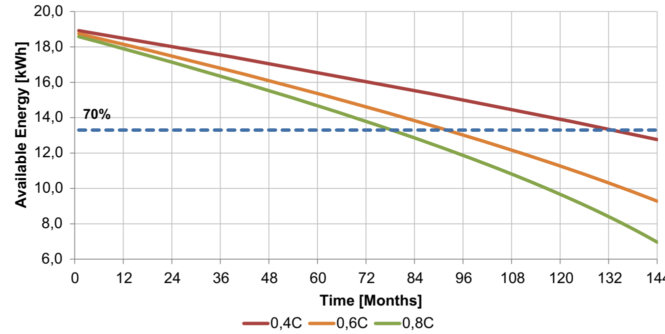

Fig. 3. Capacity loss over time for an initial available capacity of 19 kWh (24 kWh in total) for different discharge rates.

The battery pack is managed by a BMS, which strict controls the temperature and the SoC, and taking into account the LMO battery chemistry, it is expected that the battery pack can perform 1000–1500 cycles at 80% of DoD and a calendar life up to ten years.

The energy that can be extracted from a battery depends on the discharge current, commonly referred in terms of C-Rate (which expresses the ratio between the charge/discharge rate and the capacity of a battery). In order to define vehicle battery use scenarios, data gathered both from real world driving scenarios [12] and from the battery manufacturer [33] was used to determine the stress imposed to the battery in terms of charge and discharge current (C-rate) and estimate the available energy under a given driving profile. This parameter is important since it is used to obtain the total energy mobilized by the battery pack during its use in the EV.

To assess the energy consumption of the battery during its use in the vehicle, a data acquisition system was installed in a Nissan Leaf. Real world driving cycles were performed in two predefined routes, one urban and other suburban, under different driving conditions (aggressive, normal and ECO) and with different settings for the climate control (A/C OFF, A/C in cooling mode and A/C in heating mode). Details on the elevation profiles of the two routes as well as on the installed system and measurements performed can be found in Ref. [12]. The energy losses in the battery were characterized as well as the additional losses in the charging station and electricity transmission and distribution system, which are usually about 9–10% [34–36]. Table 1 summarizes the energy efficiency along its conversion pathway.

Table 2 classifies the driving profiles assessed, considering the average discharge current of the battery pack in terms of C-rate and energy consumption. Three driving profile scenarios were defined: i) light use, corresponding to an average discharge C-rate of 0.4C (104 Wh km^{-1}); ii) moderate use, with an average discharge C-rate of 0.6C (167 Wh km^{-1}); and iii) intensive user, characterized by an average discharge C-rate of 0.8C (213 Wh km^{-1}). The contribution of the driving profile to the capacity degradation is related to the number of cycles required to travel a given distance. An intensive use requires a higher number of cycles to travel the same distance than a lighter use, due to higher energy consumption and losses and lower energy extracted from the battery. For an intensive use,

Table 3
Total mobilized energy and traveled distance during in-vehicle battery use under different discharge profiles.

	0.4C	0.6C	0.8C
Total mobilized energy (kWh/battery)	14736	17271	17768
Total distance (km/battery)	165000	113750	97500
Number of cycles per battery (C_{curr} = 70%.C_{ini})	1070	1258	1302
Number of batteries for 200000 km	1.21	1.76	2.05

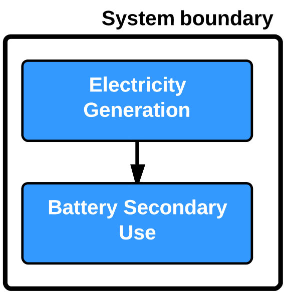

Fig. 4. System boundary of the battery life-cycle model for secondary use (energy storage in buildings).

the main contributor to capacity degradation is cycle aging, while, for a light use, it is the calendar aging. A more detailed description of how energy consumption is affected by the driving profile can be found in Ref. [37].

Considering the C-Rates from Table 2 and the discharge curves from Fig. 2, the capacity available to the user is: 18.96 kWh at 0.4C; 18.8 kWh at 0.6C and 18.64 kWh at 0.8C. It should be noted that despite the battery pack being able to store 24 kWh, only 19 kWh are in fact available to be spent by the user. This value was obtained experimentally by running the EV until the range reached zero km and measuring the total amount of energy required to fully charge the battery, taking into consideration the losses on the battery and inverter.

It was assumed that the EV battery pack reaches the end of its in-vehicle life when the capacity drops to 70% (13.3 kWh) of the initial capacity [38]. Considering the manufacturer warranty (160000 km or 8 years, whichever comes first) before a capacity drop bellow 70% under normal use, the considered capacity loss due to cycling (A_{cyc}) is 3 Wh per cycle, while the capacity loss due to calendar aging (A_{cal}) is 0.6 Wh per day. These values were chosen assuming that the temperature of the battery pack is kept constant during the entire life cycle of the EV and it is always discharged to 80% of DoD. Cycling and calendar aging is taken into account to assess the loss of capacity over time, which is calculated using Eq. (1).

$$C_{curr} = C_{ini} - (A_{cal} \cdot t + A_{cyc} \cdot N) \quad (1)$$

where C_{ini} and C_{curr} define the initial and current battery capacity (in Wh), respectively; A_{cal} (in Wh day^{-1}) and A_{cyc} (in Wh cycle^{-1}) define the aging coefficients for calendar and cycle aging, respectively; t is the time in days since the battery as started to be used

Table 4
Daily energy consumption, peak power and energy storage requirements for the peak shaving application for the considered household per day, taking into account the seasonal variation of the load diagram. The peak energy corresponds to the amount of energy above the average daily consumption. The storage requirements are the required storage capacity to supply the peak energy taking into account the battery charge and discharge efficiency (Table 1).

	Daily consumption (kWh)	Peak power (kW)	Storage requirements (peak shaving) (kWh)
Winter	36.58	5.98	5.98
Spring	29.22	3.63	3.63
Summer	33.57	3.43	3.43
Autumn	30.97	4.10	4.10

and N corresponds to the number of cycles that the battery has being subjected to. The energy required to fully charge the battery at a given point of the service life, by the power plant, is given by Equation (2):

$$E_{req} = C_{curr} \cdot \left(1/\eta_{charge}\right) \cdot \left(1/\eta_{t\&d}\right) \quad (2)$$

where η_{charge} and $\eta_{t\&d}$ are the efficiencies associated with the battery charging and discharging process and electricity transmission and distribution, respectively.

A traveled distance of 15000 km per year (around 40 km per day), the available capacity based on the driving profile and the battery aging were considered to calculate the required number of cycles, per day, and respective energy.

Fig. 3 shows the capacity loss over time for the different driving profiles. The driving profiles are represented in terms of C-Rate and can be translated in terms of energy consumption by referring to Table 2. As expected, a more intensive use leads to a shorter service life for the EV battery pack due to a higher cycling rate, which contributes more to capacity reduction than calendar aging. A lighter use maximizes the service life of the battery pack due to a lower number of cycles and a more efficient use of the energy.

Table 3 summarizes the total energy required by the battery pack during its service life in the EV (i.e. until it reaches 70% of its initial capacity) and the total traveled distance per battery pack for the three scenarios. As can be seen, a battery pack cycled at 0.4C allows the vehicle to travel more 70% than a battery pack cycled at 0.8C, and requires 17% less energy. Since neither of the use profiles will be able to reach the 200000 considered for the EV life cycle, more than one battery will be required. From the traveled distance per battery pack, it is possible to calculate the amount of battery packs required during the vehicle service life, which is the reference flow for each scenario.

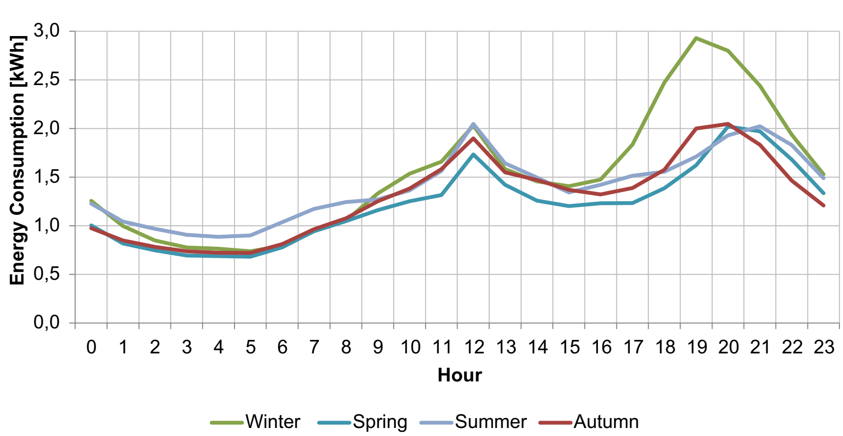

Fig. 5. Seasonal variation in the load diagram for the household during the second life of batteries [44].

2.2. Life-cycle model of battery secondary use — energy storage in buildings

By extending the battery life beyond its original use, its use is maximized and the introduction of new batteries in the market can be delayed, which may avoid environmental impacts and, from an economic perspective, could have the potential to offset some of the high initial cost of the battery. After their first use, the battery pack still has available storage capacity making it suitable for other applications rather than electric mobility. In this article, two scenarios of battery use for energy storage in buildings are analyzed: peak shaving and load shifting. It is assumed that the battery pack used for energy storage still retains 70% (13.3 kWh) of its initial capacity in all scenarios and is used until the capacity drops to 50% (9.5 kWh) [38].

The system boundary for the assessment of the environmental impacts of the secondary use (energy storage in a household) of the battery pack is presented in Fig. 4. The impacts associated with the battery production and end of life were attributed to the primary use since the primary function of the battery pack is to be used in the EV. Thus, it is assumed that the battery pack goes to the second use free from environmental burdens (i.e. it is considered a residue). The model includes the generation of electricity required to fulfill the electricity needs of a household for both scenarios, including the additional losses in the battery. The benefits (or impacts) of giving a second life to the battery are assessed against a Business-as-Usual (BaU) scenario, i.e. in which the household electricity requirements are satisfied directly from the grid.

The energy consumption in a household varies significantly during the day and with the season. To take these variations into account, average load diagrams for a 24 h period for the four seasons are used in the calculations and are presented in Fig. 5. The load diagrams are based on [32] and characterize the typical power consumption in a European 3 to 4 bedroom household. The electricity generation modeling is performed as explained in Section 2.3.

2.2.1. Energy storage scenarios

Two scenarios of secondary use of the battery for energy storage in buildings are analyzed: peak shaving and load shifting. For both scenarios, the battery is charged at night, when the contribution of RESs is usually higher, and the electricity stored is supplied during the day. The discharge phase for the peak shaving scenario occurs only during residential peak periods in opposition to the load shifting scenario in which the discharge phase is distributed along the day. From the grid point of view, both scenarios contribute to a more constant load diagram over time and to a reduction of the power demand in peak hours. By having a more constant and predictable load diagram, it is possible to manage the power plants to work near their nominal capacity, which is beneficial both from an economical and from an environmental point of view [39–41].

Based on the load diagrams, the requirements in terms of storage capacity for a peak shaving application correspond to the energy above the average daily consumption. This amount of energy is supplied by the battery, which is charged during the night when the household energy consumption is lower. The energy storage requirements in each season are summarized in Table 4. The calculation of the storage requirements took into account the energy loss during the charge and discharge processes both on the battery and the inverter. For the load shifting application, since the daily energy consumption is always higher than the battery pack available capacity, the battery is cycled once a day. Since the energy consumption varies with season, the seasonal variation in the energy consumption is also taken into account.

Fig. 6 presents the capacity loss over time for both scenarios. After the first use, the battery pack has 13.3 kWh available capacity. However, due to efficiency losses during the discharge process and in the inverter, only about 12 kWh are available to be used. It is assumed that the battery is no longer suitable when capacity drops to 50% (9.5 kWh) of its initial capacity, due to significant voltage losses due to the aging process. Considering the household energy requirements, a battery pack will have a second life of 1.8 years if used for load shifting and 3.3 years if used for peak shaving.

On Table 5 the mobilized energy, from night to the day, during the second life of the battery pack for the different usage scenarios is presented. In the peak shaving scenario, the battery pack is used longer than in the load shifting scenario, since it is cycled less frequently. In the load shifting scenario, the energy consumption

Table 5
Mobilized energy, residual capacity and number of cycles for the second life of the battery pack, under different scenarios, at the plug and the required generation at the power plant.

	Load shifting	Peak shaving
Mobilized energy (kWh)	8559	8224
Residual capacity (kWh)	9.5	9.5
Number of cycles	660	572
Years	1.8	3.3

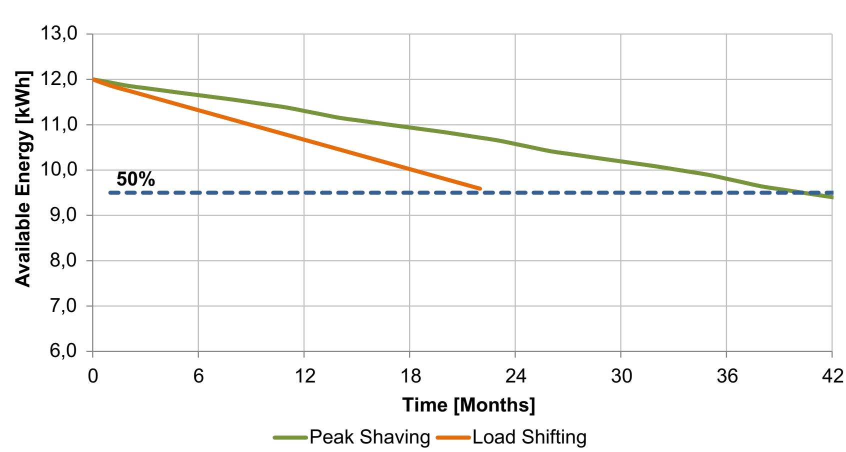

Fig. 6. Storage capacity available over time for the second life of an electric mobility battery pack used in a peak shaving and load shifting application. For the second life, the battery pack has an initial capacity of 13 kWh, from which only around 12 kWh are available, taking into account the discharge efficiency. The battery is no longer suitable when the capacity drops to 9.5 kWh (50% of the initial available capacity).

Table 6
Life-cycle environmental impacts by technology (average European technologies) [45].

Technology	Abiotic depletion (g Sb eq kWh^{-1})	Acidification (g SO_2 eq kWh^{-1})	Eutrophication (g PO_4^{3-} eq kWh^{-1})	Global warming (g CO_2 eq kWh^{-1})
Coal	7.8	2.8	2.3	1020
Wind	0.08	0.05	0.027	11.3
Hydroelectric	0.03	0.16	0.05	6.5
Solar PV	0.36	0.246	0.157	50.9
Nuclear	0.04	0.047	0.015	6.05
Natural Gas	3.7	0.413	0.07	434
Diesel, Oil	5.9	19	0.57	911

per day is higher than the available storage capacity and the battery is subject to a full charge/discharge cycle per day.

2.3. Life-cycle model of electricity generation and scenarios

The environmental impacts associated with battery use are directly related to electricity generation. The electricity generation mix varies from region to region and in a daily and seasonal basis, due to variations in RESs [42]. Due to this, three European electricity mixes were considered (Polish, Portuguese and French, in 2011), taking into account their daily and seasonal variation. The electricity mixes were chosen based on the high share of fossil (Poland), high share of renewable (Portugal) and high share of nuclear (France) energy sources. The electricity mix for the three scenarios is presented in Fig. A.7 of the Supplementary data.

The impacts associated with electricity generation are calculated taking into account the emissions from Table 6, which represent the life-cycle impacts of average European technologies, and the daily variation during a year for the different energy sources that contribute to the mix (Fig. A.7 in Supplementary data).

The impacts in each category vary considerably over the year and also during the day for the mixes with a significant share of RESs or Nuclear (Figs. A.8–A.11, in the Supplementary data). Due to the intermittent characteristic of wind and solar photovoltaic sources and their significant share in the generation mix, hydro and fossil power plants must be kept in standby to compensate the variations in the production from these sources, which may lead to higher emissions [43]. For a mix based mainly on fossil fuel power plants, the associated emissions are fairly constant over the year and over the day.

3. Results and discussion

3.1. Life-cycle environmental impacts of primary use

In this section, the environmental impact associated with the battery pack is assessed taking into account its use in electric mobility applications. For the primary use, it was assumed that the EV reaches its end of life after 200000 km. Table 7 summarizes the environmental impacts of the production and end-of-life phase of the battery pack. The battery manufacturing and disposal phases are common to all the considered scenarios, since they are independent from the use phase. The anode is the component with the highest contribution in Eutrophication (59%) and Acidification (45%), while the cathode contributes the most to Global Warming (37%) and Abiotic Depletion (28%). The pack has the second largest contribution to the impacts in all categories (23%–29%).

Table 8 presents the LC environmental impacts per km associated with the operation of the vehicle during its service life, for each impact category, under different mixes and charging scenarios. A light use (0.4C) has 42–50% less impacts per km than an intensive use (0.8C), depending on the impact category and generation mix. For these results contribute the fact that a light use reduces by around 40% the battery capacity fade, which from an LCA perspective, translates in a reduction in the same proportion of the production and disposal impacts (i.e less batteries are required). Additionally, in terms of energy, a light use requires less 17% of energy when compared with an intensive use, to perform the same distance. The French mix scenario has the lowest environmental impacts in all categories (e.g. for Global Warming, a reduction of 64–67% compared to the Portuguese mix and 88–89% compared to the Polish mix). The charging period has higher influence in the results for the French mix (9–10% difference between day and night charging for Global Warming and Abiotic Depletion and 6% for Acidification). For the Portuguese and Polish mix, the difference is less than 5%. As expected a lighter use (0.4C) will have a lower impact over all the impact categories when compared with a more intensive use (0.8C), despite under light use the total traveled distance being the highest.

3.2. Life-cycle environmental impacts of secondary use

In this section, the environmental impacts of using a battery pack from an EV for energy storage in a household, are assessed, considering a peak shaving and load shifting application. By observing the load diagrams from Fig. 5, it is noticeable that the household energy consumption is concentrated at the end of the afternoon and beginning of the night, with some occurrences

Table 7
Life-cycle environmental impacts associated with the production and end-of-life of an LMO battery pack with 300 kg and a capacity of 24 kWh.

		Abiotic depletion (kg Sb eq $batt.^{-1}$)	Acidification (kg SO_2 eq $batt.^{-1}$)	Eutrophication (kg PO_4^{3-} eq $batt.^{-1}$)	Global warming (kg CO_2 eq $batt.^{-1}$)
Cells	Anode	3.2	8.1	9.1	221.4
	Separator	0.6	0.4	0.1	74.2
	Cathode	4.0	2.6	1.2	633.5
	Electrolyte	1.4	2.2	0.4	166.0
Other		1.2	0.8	0.2	136.5
Pack		3.7	4.1	4.4	470.4
Production (total)		14.1	18.2	15.4	1702
End of Life		2.4	5.7	1.0	389.1

Table 8
Life-cycle environmental impacts, per km, for different driving profiles (0.4, 0.6 and 0.8C), electricity mixes (France, Portugal, and Poland) and charging period (night and day charging). Includes impacts from battery production and end-of-life as well as vehicle operation impacts.

			Abiotic depletion (kg Sb eq km^{-1})	Acidification (kg SO_2 eq /km^{-1})	Eutrophication ((kg PO_4^{3-} eq km^{-1}))	Global warming (kg CO_2 eq km^{-1})
France	0.4C	Night Ch.	1.65	0.18	0.11	18.84
		Day Ch.	0.16	0.19	0.12	20.65
	0.6C	Night Ch.	0.23	0.27	0.17	28.96
		Day Ch.	0.25	0.29	0.17	31.98
	0.8C	Night Ch.	0.27	0.32	0.19	34.18
		Day Ch.	0.30	0.34	0.20	37.82
Portugal	0.4C	Night Ch.	0.41	0.22	0.17	51.81
		Day Ch.	0.43	0.23	0.17	54.25
	0.6C	Night Ch.	0.68	0.34	0.26	84.67
		Day Ch.	0.71	0.35	0.27	88.91
	0.8C	Night Ch.	0.80	0.40	0.31	100.52
		Day Ch.	0.84	0.41	0.32	105.61
Poland	0.4C	Night Ch.	1.24	0.96	0.22	153.15
		Day Ch.	1.26	0.97	0.23	155.10
	0.6C	Night Ch.	2.09	1.60	0.35	257.93
		Day Ch.	2.12	1.62	0.36	261.24
	0.8C	Night Ch.	2.50	1.91	0.42	308.45
		Day Ch.	2.54	1.94	0.43	312.42

during the morning period, being this the period in which the battery will supply energy. The environmental impacts of electricity generation depend on the time of the day and the season, which varies from country to country. From the three mixes previously analyzed, only the mixes from Portugal and France are considered, since a mix with constant share of energy sources during the day, as in Poland, has always higher overall impacts from battery use compared to the BaU scenario, due to the efficiency losses during battery charge and discharge processes. The additional impacts from battery use, in the Polish case, are proportional to the charge/discharge efficiency losses (22%).

Table 9 presents the LC environmental impacts for the two scenarios of secondary use of the battery compared to the respective BaU scenario (without battery). The impacts are calculated taking into account the time of charging and the additional losses in the battery and inverter. As can be seen, the battery use to shift energy consumption from peak to off-peak periods may be beneficial, depending on the electricity generation mix, even accounting for the efficiency losses from battery use. For a mix in which environmental impacts from electricity generation at night are lower than during the day and this difference is higher than the additional efficiency losses (22%), such as the French mix, using the battery is beneficial. The reduction of environmental impacts from battery use in the French scenario varies between 2% for peak shaving and 4–5% for load shifting. On the other hand, for the Portuguese mix, using the battery for household energy storage is not beneficial, as the overall environmental impacts from electricity generation at night are not low enough to compensate the additional energy consumption due to battery efficiency loss. For this scenario, using the battery increases the impacts by 1–2% for load shifting and 3% for peak shaving.

Moreover, the results presented are aggregated impacts (or benefits) for the entire battery service life in the household. Disaggregated results, presented in Fig. A.12–A.15 in Supplementary data, show that the impacts (or benefits) vary along the year. Therefore, to accomplish an overall reduction of environmental impacts, a more complex strategy should be implemented, in which a prediction of the generation share for the different energy sources should be taken into account. Based on this prediction, the optimal period to charge and discharge the battery could be determined, or the battery use could be avoided in the case of impacts. From an environmental point of view, for the energy shift become beneficial the emissions at night must be lower than the emissions during the day by a factor identical to the efficiency loss in the battery charge/discharge process (if the efficiency loss is 22%, then the emissions at night must be 22%, or more, lower than during the day).

3.2.1. Economic analysis

From an economic point of view, the shifting energy from peak hours to non-peak hours allows savings, even with the loss of efficiency in the charge/discharge process of the battery. If the battery use is maximized, by charging the battery during off peak periods (usually at night), when energy is cheaper, and discharge the full capacity during peak periods (during the day), the savings would be greater.

Considering the Portuguese tariff, where the cost of 1 kWh during the peak periods is 0.14 € and during off peak periods is 0.07 €, shifting 1 kWh to off peak periods will cost 0.084 € which corresponds to a 40% saving (this energy shift will require and additional 0.22 kWh per kWh due to efficiency loss).

It should be taken into account that an additional cost is required for the setup of the storage system as well the acquisition

Table 9
Life-cycle environmental impacts during the secondary use of the battery for the peak shaving (PS) and load shifting scenarios (LS).

		Abiotic depletion (kg Sb eq)		Acidification (kg SO_2 eq)		Eutrophication (kg PO_4^{3-} eq)		Global warming (kg CO_2 eq)	
		Portugal	France	Portugal	France	Portugal	France	Portugal	France
PS	w/out Battery	96.93	18.70	22.55	13.48	20.74	4.82	12.00	2.40
	w/Battery	100.00	18.39	23.56	13.26	21.45	4.74	12.40	2.36
	Δ%	3	−2	4	−2	3	−2	3	−2
LS	w/out Battery	53.47	9.07	13.28	6.60	11.85	2.32	6.67	1.17
	w/Battery	54.57	8.65	13.59	6.29	11.99	2.22	6.81	1.11
	Δ%	2	−5	2	−5	1	−4	2	−5

Table 10
Prices, by season, for regulation and spinning reserve ancillary services in the Iberian electricity market during 2011 [46].

	Regulation (€ MWh^{-1})		Spinning reserve (€ MWh^{-1})	
	Average	Standard deviation	Average (up/down)	Standard deviation (up/down)
Winter	29.92	16.80	58.27/17.00	16.52/17.00
Spring	22.70	5.73	57.15/21.67	10.12/17.78
Summer	28.01	5.88	68.95/27.34	17.63/16.32
Autumn	32.09	8.57	76.31/29.84	23.18/23.30

of a bidirectional inverter. Considering this additional cost of about 3000 €, this energy storage solution is only viable by providing ancillary services to the grid. These services are only required from the grid a few hours per year but must be available to system operators 24 h per day 7 days per week, and thus can take the advantage from the energy storage system. The two specific ancillary services for which a market exist, and particularly suitable for a battery energy storage, are regulation and spinning reserves. Depending on the power and capacity available, these services could provide an additional revenue shown in Table 10. The price paid for these services varies significantly during the day and by season, leading to a large uncertainty regarding the revenue that an user can obtain by providing these services for the grid. Since the grid require a given capacity available 24/7, this revenue will also depend on the capacity that the user will assign to these services.

Since the revenue is associated with the capacity assigned to the grid, a household with a peak shaving application has the possibility to obtain a higher revenue, since is the one with the lowest requirements for energy storage, opposed to a load shifting application that requires the full battery capacity.

Although in terms of environmental impacts this solution is not always beneficial, from an economic point of view both the consumer and the grid may have advantages. By using a battery the consumer can reduce its electrical bill and can provide an ancillary service for the grid, which is paid based on the battery power and capacity available after the storage requirements being met. The grid will benefit from this approach by having at its disposal an energy storage device with a very fast response time that could be used for voltage and frequency regulation. Additional benefits include a more constant consumption profile during the day and a storage solution useful for RESs integration.

4. Conclusions

By extending the life of a battery pack previously used in an electric mobility application, through a second life application in residential energy storage, reductions of environmental impacts can be achieved, due to load shifting from consumption peaks.

The environmental impacts associated with the battery use for energy storage in a household are directly related to the electricity generation mix. Even for a mix with a large share of RESs, its use could lead to higher emissions, when compared with a situation where no battery is used for energy storage. Due to efficiency loss in the charging and discharging process, the difference between night and day time impacts of electricity generation may not be sufficient to reduce environmental impacts, even in a mix with high share of RESs such as the Portuguese mix. For a small difference, this solution can even be worse than the BaU approach. In this case, a more intelligent approach should be implemented where a prediction between night and day time impacts is taken into account and the energy storage is only used when environmental impacts have the potential to be reduced.

Residential energy storage can also be beneficial to the grid since the battery packs, if deployed in a significant number, can be used to provide ancillary services which can reduce the amount of conventional power plants that provide this service and contribute to a reduction of the overall electricity generation impacts. From the economic stand point of view, this solution brings benefits to the consumer by shifting energy from a cheaper period to a more expensive one and by having the ability to provide regulation services to the grid. However, the corresponding viability will depend on the resale value of the batteries and on the implemented storage strategy.

Acknowledgments

This work was supported by Foundation for Science and Technology (FCT) under the projects MIT/MCA/0066/2009 (Economic and Environmental Sustainability of Electric Vehicle Systems), CENTRO-07-0224-FEDER-002004 (Energy and Mobility for Sustainable Regions) and PTDC/SEN-TRA/117251/2010. This research is framed under the Energy for Sustainability Initiative of the University of Coimbra and was supported by the FCT, through the MIT PORTUGAL program. The FCT doctoral grant SFRH/BD/51299/2010 is also acknowledged.

Glossary

BEV	battery electric vehicle
BMS	battery management system
BaU	business-as-usual
DoD	depth of discharge
EU	European union
EV	electric vehicle
GW	global warming
GHG	greenhouse gas
LC	life-cycle
LCA	life-cycle assessment
LMO	lithium manganese oxide
PHEV	plug-in hybrid electric vehicle
RES	renewable energy source
SoC	state of charge
SoH	state of health

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jpowsour.2014.03.092.

References

[1] J.V. Mierlo, G. Maggetto, P. Lataire, Energy Convers. Manage. 47 (17) (2006) 2748–2760, 12th International Conference on Emerging Nuclear Energy Systems.
[2] B. Scrosati, J. Garche, J. Power Sources 195 (9) (2010) 2419–2430.
[3] M. Leuenberger, R. Frischknecht, Life Cycle Assessment of Battery Electric Vehicles and Concept Cars, Report, E. Services Ltd., June 2010. http://www.esu-services.ch/.
[4] M. Weiss, M.K. Patel, M. Junginger, A. Perujo, P. Bonnel, G. van Grootveld, Energy Policy 48 (2012) 374–393.
[5] C. Samaras, K. Meisterling, Environ. Sci. Technol. 42 (9) (2008) 3170–3176.
[6] L. Gaines, J. Sullivan, A. Burnham, I. Belharouak, Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling, Report, August 2010.
[7] L. Lu, X. Han, J. Li, J. Hua, M. Ouyang, J. Power Sources 226 (2013) 272–288.
[8] J. Neubauer, A. Pesaran, B. Williams, M. Ferry, SAE Tech. Pap. (January 2012).
[9] B. Williams, T. Lipman, Analysis of the Combined Vehicle and Post Vehicle Use Value of Lithium-Ion Plug-In Vehicle Propulsion Batteries, Report, April 2011.
[10] International Organization for Standardization, ISO 14040: Environmental Management – Life-Cycle Assessment – Principles and Framework, 2006.
[11] International Organization for Standardization, ISO 14044: Environmental Management – Life-Cycle Assessment – Requirements and Guidelines, 2006.

[12] R. Faria, P. Marques, P. Moura, F. Freire, J. Delgado, A.T. de Almeida, Renewable Sustainable Energy Rev. 24 (2013) 271–287.
[13] F. Freire, P. Marques, in: Sustainable Systems and Technology (ISSST), 2012 IEEE International Symposium on, 2012, pp. 1–6.
[14] T. Hawkins, O. Gausen, A. Strømman, Int. J. Life Cycle Assess. 17 (8) (2012) 997–1014.
[15] J. Guinee, M. Gorree, R. Heijungs, G. Huppes, R. Kleijn, A.D. Koning, L.V. Oers, A. Wegener Sleeswijk, S. Suh, H. Udo de Haes, H.D. Bruijn, R.V. Duin, M. Huijbregts, Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards, Kluwer Academic Publishers, 2002.
[16] European Commission, Official J. L 120 (May 2009) 5–12.
[17] D.A. Notter, M. Gauch, R. Widmer, P. Wager, A. Stamp, R. Zah, H.-J. Althaus, Environ. Sci. Technol. 44 (17) (2009) 6550–6556.
[18] A. Chagnes, B. Pospiech, J. Chem. Technol. Biotechnol. 88 (7) (2013) 1191–1199.
[19] R. Hischier, M. Classen, M. Lehmann, W. Scharnhorst, Life Cycle Inventories of Electric and Electronic Equipment: Production, Use and Disposal, Ecoinvent Report 18, EMPA/Technology & Society Lab, Swiss Centre for Life Cycle Inventories, Dubendorf, 2007, pp. 71–75.
[20] P.V. den Bossche, F. Vergels, J.V. Mierlo, J. Matheys, W.V. Autenboer, J. Power Sources 162 (2) (2006) 913–919.
[21] G. Sarre, P. Blanchard, M. Broussely, J. Power Sources 127 (1–2) (2004) 65–71.
[22] A. Nuhic, T. Terzimehic, T. Soczka-Guth, M. Buchholz, K. Dietmayer, J. Power Sources 239 (2013) 680–688.
[23] J. Vetter, P. Novák, M. Wagner, C. Veit, K.-C. Moller, J. Besenhard, M. Winter, M. Wohlfahrt-Mehrens, C. Vogler, A. Hammouche, J. Power Sources 147 (1–2) (2005) 269–281.
[24] M. Ecker, J.B. Gerschler, J. Vogel, S. Kbitz, F. Hust, P. Dechent, D.U. Sauer, J. Power Sources 215 (2012) 248–257.
[25] S.S. Choi, H.S. Lim, J. Power Sources 111 (1) (2002) 130–136.
[26] M. Broussely, S. Herreyre, P. Biensan, P. Kasztejna, K. Nechev, R. Staniewicz, J. Power Sources 97–98 (2001) 13–21. Proceedings of the 10th International Meeting on Lithium Batteries.
[27] A. Barré, B. Deguilhem, S. Grolleau, M. Gérard, F. Suard, D. Riu, J. Power Sources 241 (2013) 680–689.
[28] G. Ning, B.N. Popov, J. Electrochem. Soc. 151 (10) (2004) A1584–A1591.
[29] C. Guenther, B. Schott, W. Hennings, P. Waldowski, M.A. Danzer, J. Power Sources 239 (2013) 604–610.
[30] L. Lam, P. Bauer, Power Electron. IEEE Trans. 28 (12) (2013) 5910–5918.
[31] R. Peng, M. Pedram, Very Large Scale Integr. (VLSI) Syst. IEEE Trans. 14 (5) (2006) 441–451.
[32] S.B. Peterson, J. Apt, J. Whitacre, J. Power Sources 195 (8) (2010) 2385–2392.
[33] Automotive Energy Supply Corporation, Lithium-ion Cell: High Energy Cell, April 2013. URL, http://www.eco-aesc-lb.com/en/product/liion_ev.
[34] K. Bayindir, A. Teke, M. Gözüküçük, Energy Convers. Manage 52 (2) (2011) 1305–1313.
[35] M. Gabriel, SAE Int. (2004).
[36] S. Campanari, G. Manzolini, F.G. de la Iglesia, J. Power Sources 186 (2) (2009) 464–477.
[37] R. Faria, P. Moura, J. Delgado, A.T. de Almeida, Energy Convers. Manage 61 (2012) 19–30.
[38] S. Thein, Y.S. Chang, J. Power Sources 249 (2014) 142–147.
[39] W. Kempton, J. Tomic, J. Power Sources 144 (1) (2005) 280–294.
[40] M. Fasugba, P. Krein, in: Energy Conversion Congress and Exposition (ECCE), 2011 IEEE, 2011, pp. 827–834.
[41] D. Freund, M. Lützenberger, S. Albayrak, Procedia Comput. Sci. 10 (2012) 846–853.
[42] O. van Vliet, A.S. Brouwer, T. Kuramochi, M. van den Broek, A. Faaij, J. Power Sources 196 (4) (2011) 2298–2310.
[43] P.S. Moura, A.T. de Almeida, Renewable Sustainable Energy Rev. 14 (5) (2010) 1461–1468.
[44] A. de Almeida, P. Fonseca, R. Bandeirinha, T. Fernandes, R. Araújo, U. Nunes, Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe, Report, September 2008.
[45] Swiss Centre for Life Cycle Inventories, Ecoinvent Centre, July 2011, URL http://www.ecoinvent.org/database/.
[46] REN, Electric Energy Information Markets, 2013, URL http://www.mercado.ren.pt/EN/Electr/MarketInfo.